What can we learn from an improved search for free N-N-bar Oscillation ?

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Two ways to probe physics beyond standard model

- Direct search e.g in colliders such as LHC.
- Indirectly by searching for rare processes forbidden in SM.

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{M}\mathcal{O}^5 + \frac{1}{M^2}\mathcal{O}^6 + \ldots + \frac{1}{M^n}\mathcal{O}^{4+n}$$

- One such rare effect is the neutrino mass, $(LH)^2$ –d=5 M not known yet. **Has B-L=2**
- Another class of processes- those violating baryon number: p-decay, NNbar osc.

What new physics they reveal

(i) d=6 operators (Weinberg; Wilczek, Zee'79) B-L=0

$$\mathcal{O}_1 = (d^c u^c)^*(Q_i L_j)\epsilon_{ij}, \quad \mathcal{O}_2 = (Q_i Q_j)(u^c e^c)^*\epsilon_{ij}, \quad \mathcal{O}_3 = (Q_i Q_j)(Q_k L_l)\epsilon_{ij}\epsilon_{kl}$$

$$\mathcal{O}_4 = (Q_i Q_j)(Q_k L_l)(\vec{\tau}\epsilon)_{ij}\cdot(\vec{\tau}\epsilon)_{kl}, \quad \mathcal{O}_5 = (d^c u^c)^*(u^c e^c)^* .$$

- Leads to $p \to e^+ + \pi^0; p \to K^+\bar{\nu}$ canonical GUTmodes
- Current data bound the mass scale M>10^{15} GeV
- They arise in GUT models with predictions (with uncertainties) and has spurred experimentalists to look for them for the last 30 years.

B-L=2 B-violation

(ii) d=7 : Have B-L=2 (Weinberg; Weldon, Zee'80)

$$\tilde{\mathcal{O}}_1 = (d^c u^c)^*(d^c L_i)^* H_j^* \epsilon_{ij}, \qquad \tilde{\mathcal{O}}_2 = (d^c d^c)^*(u^c L_i)^* H_j^* \epsilon_{ij},$$

$$\tilde{\mathcal{O}}_3 = (Q_i Q_j)(d^c L_k)^* H_l^* \epsilon_{ij}\epsilon_{kl}, \qquad \tilde{\mathcal{O}}_4 = (Q_i Q_j)(d^c L_k)^* H_l^* (\vec{\tau}\epsilon)_{ij} \cdot (\vec{\tau}\epsilon)_{kl},$$

$$\tilde{\mathcal{O}}_5 = (Q_i e^c)(d^c d^c)^* H_i^*, \qquad \tilde{\mathcal{O}}_6 = (d^c d^c)^*(d^c L_i)^* H_i,$$

$$\tilde{\mathcal{O}}_7 = (d^c D_\mu d^c)^*(\overline{L}_i \gamma^\mu Q_i), \qquad \tilde{\mathcal{O}}_8 = (d^c D_\mu L_i)^*(\overline{d^c}\gamma^\mu Q_i),$$

$$\tilde{\mathcal{O}}_9 = (d^c D_\mu d^c)^*(\overline{d^c}\gamma^\mu e^c)\ .$$

$\rightarrow$ $n \rightarrow e^- \pi^+$

(iii) d=9: $u^c d^c d^c u^c d^c d^c$ B-L=2 $\rightarrow$ $n - \bar{n}$

(RNM, Marshak'80; Glashow'80)

- Curious feature: odd d B-L=2 and even d, B-L=0; No B-L=1 due to Lorentz invariance

Neutrino mass- NNbar connection

- Both have odd d and break B-L by 2 units;
- If neutrino is Majorana, it breaks $\mathcal{L}$-part of **B-L** by 2units
- N-N-bar oscillation breaks B-part of B-L and provides complementary information on nu mass physics
- Are there models where this happens ?
- Yes. NNbar is a generic prediction of theories where seesaw mechanism for nu mass is embedded into quark-lepton unification as in grand unified theories

Seesaw breaks $\mathcal{L}$ and Q$\mathcal{L}$ unification converts to $\mathcal{B}$=2 !

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Today's plan

- Upper bound on NNbar transition time
  Q-L unified 224 model

- Comments on GUT models and NNbar

Seesaw+Quark-lepton Unification and NN-bar

- Seesaw model for neutrino masses:
- Standard model + RH neutrino N
- Two sets of Higgs fields:

  (i) SM doublet for usual fermion masses: ϕ

  (ii) New Higgs field to give mass to RH neutrino: Δ^0_R
- $<\Delta^0>_R \neq 0$, $<\phi>\neq 0$.

$$(\nu, N)\begin{pmatrix} 0 & h<\phi> \\ h<\phi> & f<\Delta_R> \end{pmatrix}\begin{pmatrix} \nu \\ N \end{pmatrix}$$

- $m_\nu \cong (m_e)^2/M_R << m_e$ (Seesaw formula)

A unified TeV scale embedding of seesaw

- If Q-L unified at the seesaw, a model is

$$SU(2)_L \times SU(2)_R \times SU(4)_c \begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}$$

→SU(4) generalization of the seesaw Higgs field Δ_R has partners Δ_{qq} connecting to qua

→N-N-bar Feynman graph;

(Mohapatra,Marshak'80)

$$\frac{\lambda f^3 v_{BL}}{M_\Delta^6}$$

→No proton decay.

$$\tau_{n-\bar{n}} = \hbar / \delta m_{n-\bar{n}} \sim M^5 / \Lambda^6$$

- Colored seesaw partners at TeV scale→ $\tau \sim 10^{10-11}$ sec.

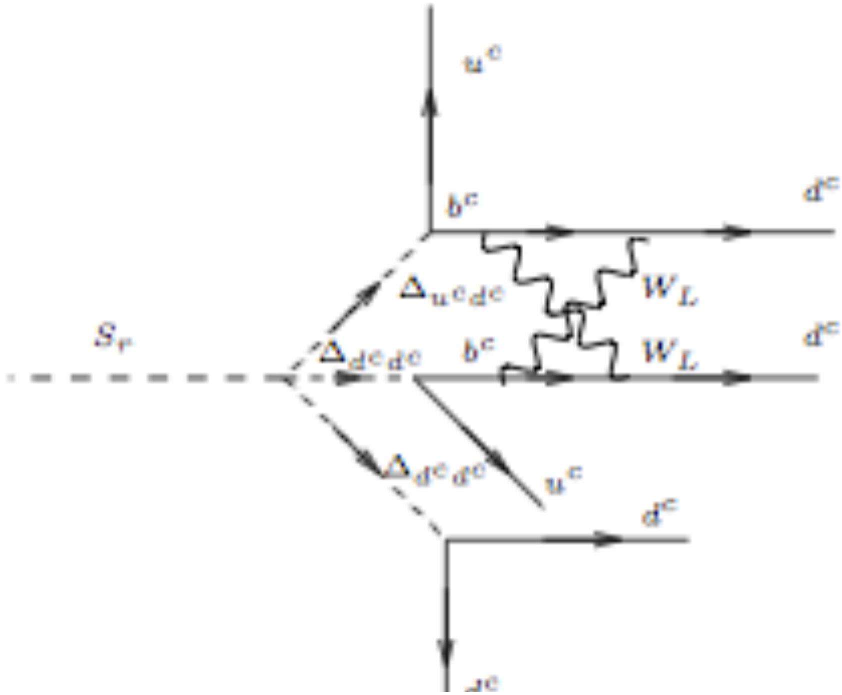
Two consequences of $SU(4)_c$

- Couplings of Δ_{qq} elements of neutrino mass matrix !!
- They lead to FCNC effects and thus constrained !!
- Is there a solution ? (Babu, Dev, RNM'09; Fortes, Babu, RNM (to appear))
- Yes, inverted hierarchy for nu masses with type II seesaw:
- Fixes coupling matrix: $f_{dd} = \begin{pmatrix} 0 & 0.95 & 1 \\ 0.95 & 0 & 0.01 \\ 1 & 0.01 & -0.063 \end{pmatrix} c$
- Masses $M_{\Delta_{dd}} \sim 10TeV; M_{\Delta_{ud}} \sim 1TeV$ satisfy all FCNC constraints
- NNbar osc loop effect; without SU(4), f_{11} arbitrary as is NNbar

Neutron-anti-neutron oscillation

- Nnbar osc. Is a loop effect:

$F_{ud} = U_{CKM} f_{dd}$



$$G_{n-\bar{n}} \simeq \frac{f_{ud,11} f_{ud,13} f_{dd,13} \lambda v_{BL}}{M^4_{\Delta_{u^c d^c}} M^2_{\Delta_{d^c d^c}}} \frac{g^4 V_{td}^2 m_b^2 m_t^2}{(16\pi^2)^2 m_W^4} \log\left(\frac{m_b^2}{m_W^2}\right)$$

Requirement of Baryogenesis

- Basic message:

(i) If all particles involved in NNbar diagram are ~TeV mass, baryogenesis must be below electroweak phase transition temp. (PSB) (Babu,Nasri, RNM'07)

(ii) Cosmology of baryogen. predicts a lower bound for $G_{n-\bar{n}}$

$G_{nn} > 10^{-31}$ GeV^{-5} → $\tau_{n\bar{n}} \leq 10^{11} sec$

(Without cosmology restrictions, scale c of the f-couplings is unknown and NNbar coupling could be anything; cosmology puts a lower bound on C~.7):

Basic outline of baryogenesis

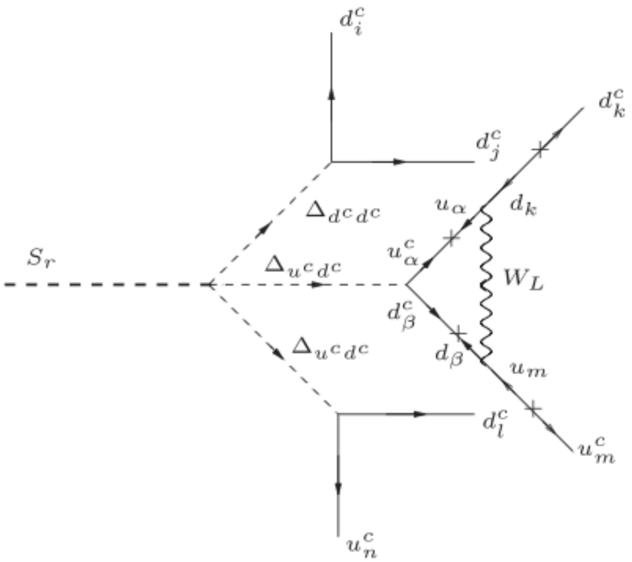
- Above EWPT → T~ v_{wk} , both B+L and B=2 violating processes in eq.→ all asymmetry erased. Need a fresh start
- Means baryogenesis must occur below EWPT
- → particle decay T_d below EWPT and above .1 GeV

$$T_d \simeq \left[\frac{36\lambda^2(\mathrm{Tr}[f^\dagger f])^3 M_{\mathrm{Pl}} M_S^{13}}{(2\pi)^9 1.66 g_*^{1/2}(6M_\Delta)^{12}}\right]^{1/2}$$

$$\simeq 6.1\ \mathrm{GeV}^{1/2}\left(\frac{M_S^{13}}{M_\Delta^{12}}\right)^{1/2}.$$

Baryogenesis diagram

- Re Δ_R decay to 6 quarks source of baryons.

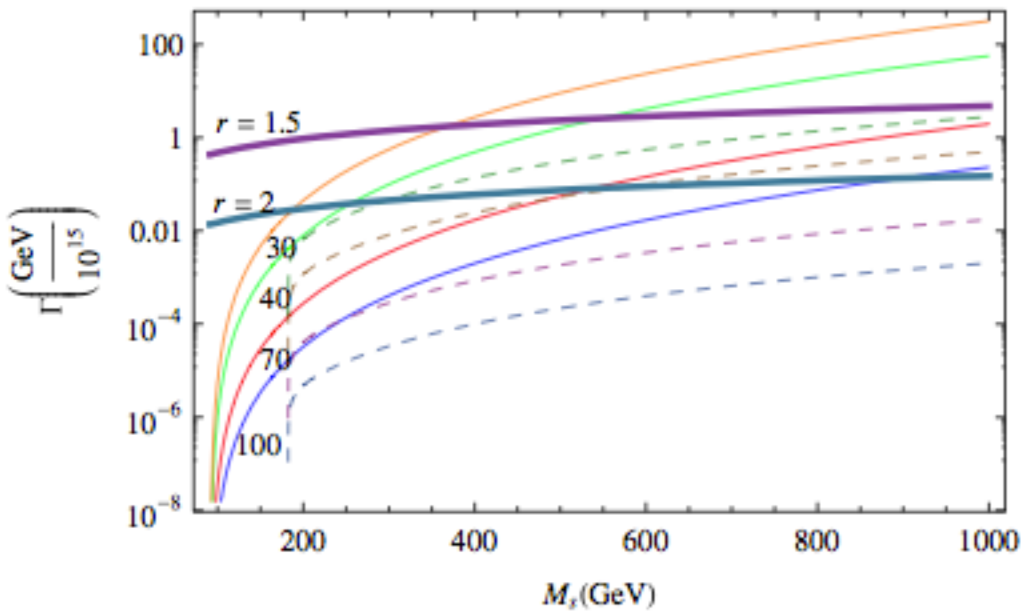


- → 6q decay must dominate over others.

Six quark decay dominance constraint

- $\Gamma_{Zf\bar{f}} \sim \dfrac{.07 M_S^5}{M_{Z'}^6} GeV$

$$\Gamma(S_r \to 6q^c) \simeq \frac{36}{(2\pi)^9} \frac{(\mathrm{Tr}[f^\dagger f])^3 \lambda^2 M_S^{13}}{(6M_\Delta)^{12}},$$

- 

v_{BL} <100 TeV

Summary of constraints

- Low scale baryogenesis in $SU(2)_L \times SU(2)_R \times SU(4)_c$ →

i) $M_{\Delta_{qq}} > M_S$

ii) $1\ GeV < T_{S-decay} < 100 GeV$

iii) $\Gamma_{S\to 6q} > \Gamma_{S\to Zq\bar{q}}$

iv) A neutrino mass fit+FCNC constraints

- These constraints upper bound NNbar transition time

$v_{BL} <$ 100 TeV $\tau < 10^{11}$ sec.

$<$ 30 TeV $\tau < 10^{10}$ sec.

Color sextet scalars and LHC connection

- FCNC, Baryogenesis → color sextet spectrum:

$$M_{\Delta_{ud}} < M_{\Delta_{dd}} << M_{\Delta_{uu}}$$

- With $M_{\Delta_{ud}} \leq TeV$

- Couples to ud, dt, bu,..
- Should show up at LHC

Production and decay

- TeVColor sextets are an inherent part of both models ; Can be searched at LHC:

(I) **Single production**: $\boxed{ud \longrightarrow \Delta_{ud} \longrightarrow tj}$

xsection calculated in **(RNM, Okada, Yu' 07;)** resonance peaks above SM background- decay to tj; B(tj) suppressed in this model.

(II) **Drell-Yan pair production** $\boxed{q\bar{q} \to G \to \Delta_{ud}\bar{\Delta}_{ud}}$

- Leads to $tjtj$ final states: **LHC reach ~ TeV**

(Chen, Rentala, Wang; Berger, Cao, Chen, Shaughnessy, Zhang' 10; Han, Lewis' 09)

Non-SUSY SO(10) –Another predictive model for NNbar

- Coupling unification fixes the mass scales as in the case of proton decay:
- In a minimal SO(10) embedding of seesaw, f_{ab} determined from fermion mass fits
- (Babu, Mohapatra'93; Fukuyama, Okada'02; Bajc, Senjanovic, Vissani'02; Goh, Mohapatra, Ng'03 Babu,Macesanu'05; Bertolini, Malinsky,Schwetz'06; Joshipura, Patel'11)
- Predicts correct θ_{23}, θ_{12} and $\boxed{\sin^2 2\theta_{13} \simeq 0.09}$
- Model has diquarks at sub-TeV scale to have unification and they lead to observable NNbar !

New Unification profile and NNbar in predictive SO(10)

- Non-SUSY SO(10) does not unify without low scale particles,
- Coupling unif with

sub-TeV $\Delta_{ud}(6,1,\frac{1}{3})$

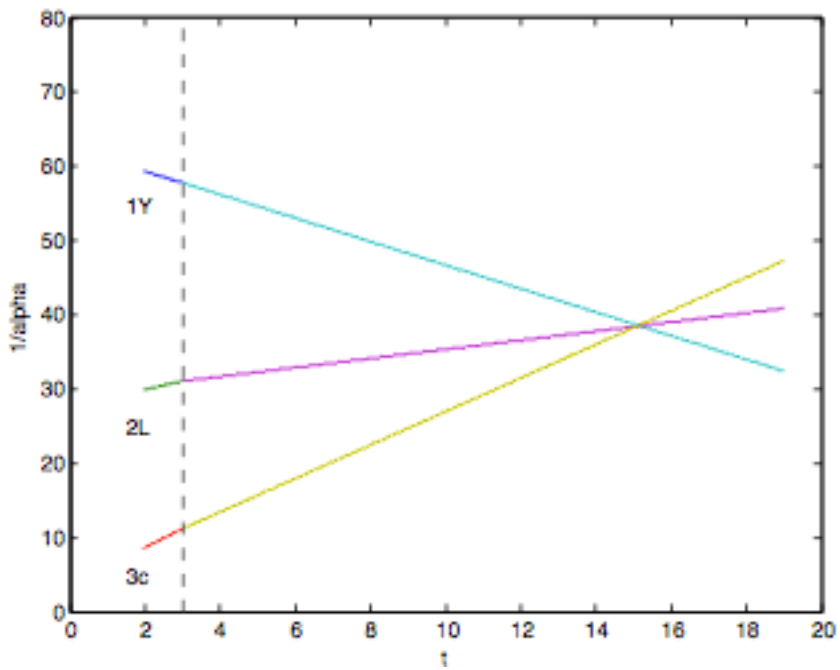
+ 2 SM triplets;

- Predicts seesaw scale

near $M_U \sim 10^{16}$ GeV;

- Δ_{ud} mass ~2 TeV
- $M_U \sim 10^{15.7}$ GeV→

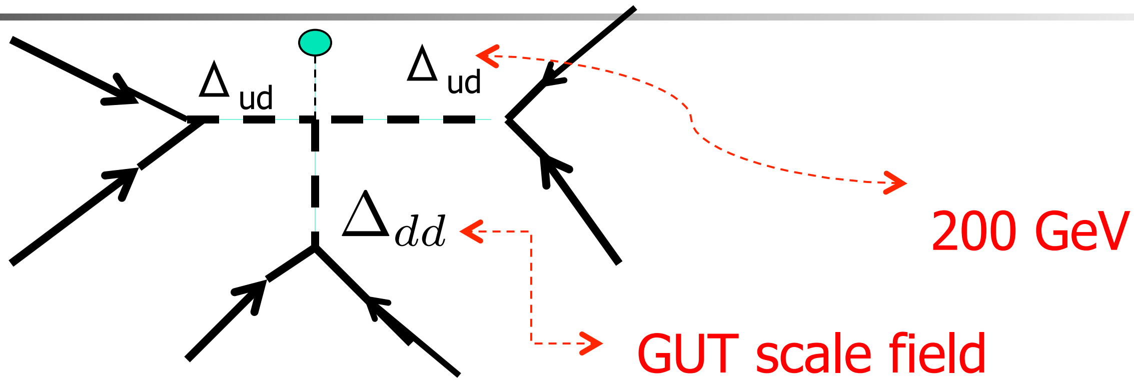
$\tau_{p\to e^+ + \pi^0} \simeq 3.2 \times 10^{34} yrs$ close to current limit.



(Babu, Mohapatra, arXiv:1206.xxxx)

Estimate of N-N-bar oscillation time

- Diagram:



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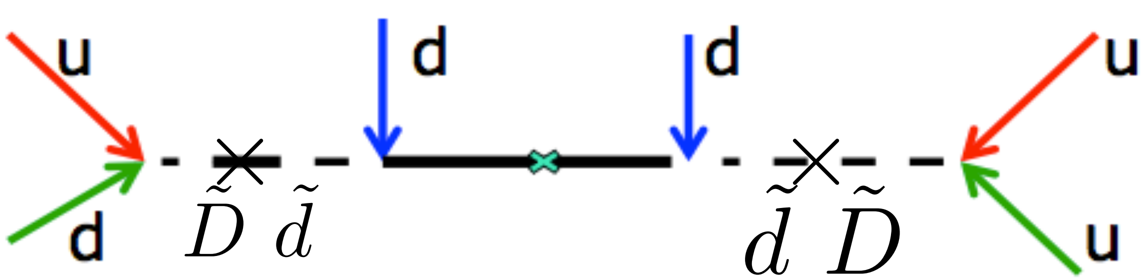
- $$G_{\Delta B=2} \simeq \frac{\lambda f_{11}^3 \eta^3}{\lambda' M_U M_{\Delta_{ud}}^4} \simeq \frac{\lambda}{\lambda'} 10^{-33} GeV^{-5}$$
- Predicts $\tau_{n-\bar{n}}$ ~10^{10} -10^{13} sec.
- Constraints of baryogenesis reduces this by two orders of magnitude. (Babu's talk)

A SUSY E_6 Model for NNbar

- E_6 contains SO(10) + extra vectorlike fermioms:
- {27}={16}+{10}+{1}
- Under SU(5), {10}={5}+ {5*} (D, E^- ,E^0)
- d-quark mixes with vectorlike D-quark and leads to Nnbar oscillation operator: not connected to nu mass: (RNM, Valle'86)



Non-SUSY E_6 –No NNbar

- Key to NNbar in SO(10)- $\{126\}^4$ coupling needed for baryogenesis.

- E_6 contains SO(10)x U(1) and this coupling is forbidden by the U(1); hence no NNbar.

Benchmark goal for ruling out new physics scenarios

- **No NNbar oscillation till ~10^{10} -10^{11} sec.**

★ Will rule out a class of $SU(2) \times SU(2) \times SU(4)_C$ models for post sphaleron baryogenesis for v_{BL} < 30-100 TeV.

★ Will rule out a class of SO(10) models for neutrino masses that predicted recently observed large θ_{13} if it is to explain the origin of matter.

THANK YOU !!

Implications of NN-bar observation for other physics

- Light color sextets →FCNC effects **e.g.**

  D0 dimuon anomaly via B-B-bar mixing and B-decay CP asym. etc. (Babu, Fortes,RNM'11)

- EDM of neutron- two loop diagram

- Strange dibaryon decay**:** NN→ KK+X (**Glashow**)

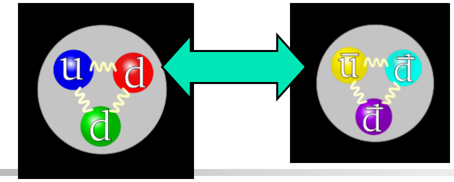
  Mediated only by $\Delta_{ud.dd}$ **Huge in our model**; recommend strange non-leptonic dibaryon decay mode search in p-decay!!

What else can we learn from direct NNbar search?

- Can test some dark matter hypothesis e.g. if a dark neutron n' is dark matter (ADM models):
- $n' \Longleftrightarrow n$ oscillation can deplete dark matter density and this can be searched for in direct nn-bar searches; current limit > 1 s. **(Bento, Berezhiani)**

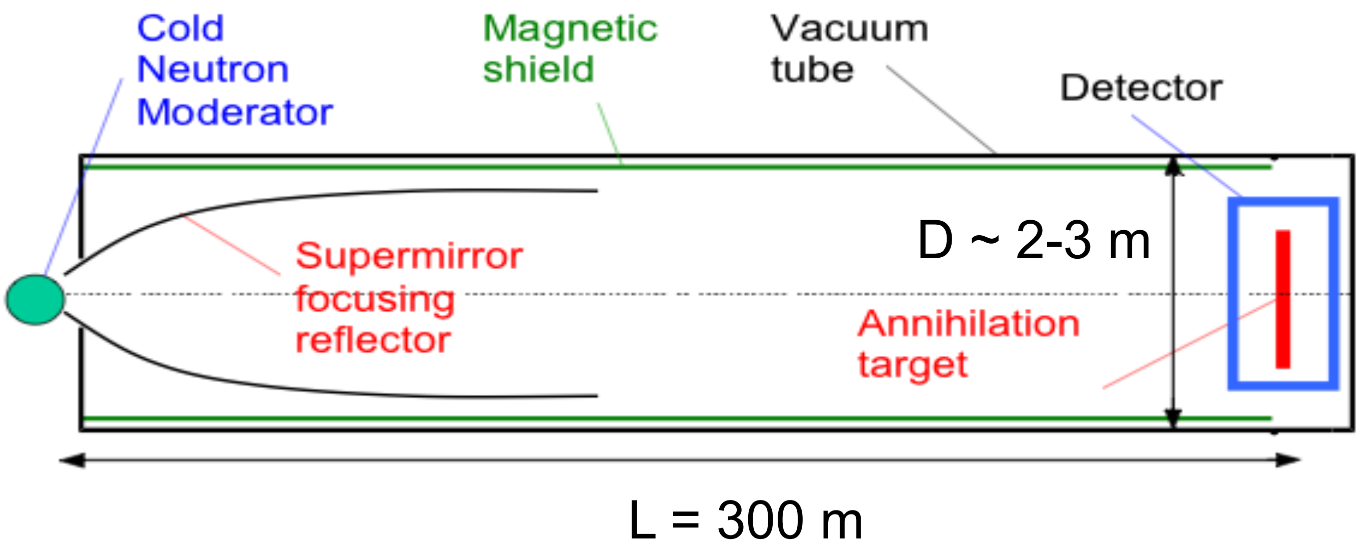
  (possibly a signal ?)
- If NNbar is discovered, it will put the strongest limit on CPT violation- **(Okun; Addazzi, BLV2011)**

Search for N-N-bar Osc. current status



- **Free neutron oscillation in reactors: generic setup**

(talks by Snow, Young)



- **Current bound (ILL' 94)**

with $L \sim 90$ m and $\langle t \rangle = 0.11$ sec

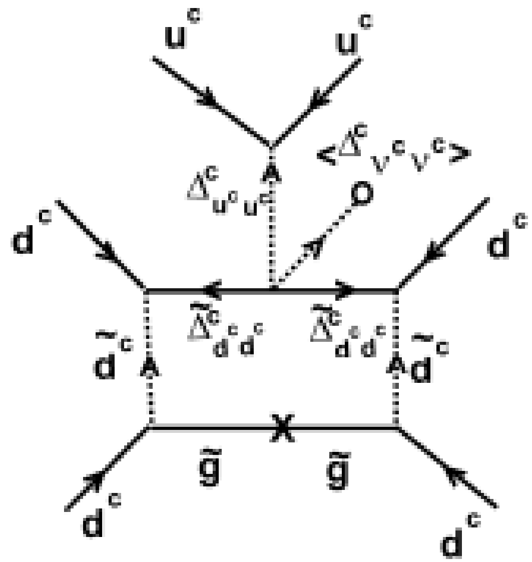
measured $P_{n\bar{n}} < 1.6 \times 10^{-18}$

$\tau > 8.6 \times 10^{7}$ sec

- **No new search after that**

Estimate of N-N-bar with susy

- **New Feynman diagram for N-N-bar osc.**



☞ $G_{N-\bar{N}} \simeq \frac{f_{11}^3}{\lambda^2 M_{seesaw}^2 v_{wk}^3}$

$M_{seesaw} \sim 10^{11}$ GeV, typical f, λ, $\tau_{N-\bar{N}} \sim 10^{10}$ sec.

Observable N-N-bar osc for M_seesaw~10^11 GeV.

(Dutta, Mimura, RNM; PRL (2006))

Scale reach of NNbar

SM particles $O_{\Delta B=2} = \frac{1}{M^5} u^c d^c d^c u^c d^c d^c$ **d=9**

Note M^5 suppression

$\delta m_{n-\bar{n}} = O_{\Delta B=2} \Lambda_{QCD}^{\ 6}$ (Lattice talks)

$\tau_{n-\bar{n}} = \hbar / \delta m_{n-\bar{n}} \sim M^5 / \Lambda^6 \rightarrow \tau_{n\bar{n}} \sim 10^8 s. \quad M \approx 10^{5.5} GeV$

TeV diquarks: $\rightarrow \Delta_{u^c d^c} \rightarrow \frac{1}{M} d^c d^c \Delta_{u^c d^c} \Delta_{u^c d^c}$

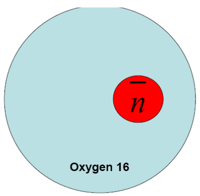
$M \simeq 10^{15} GeV$

Same scale reach as proton decay but probes different physics, more closely related to nu mass

Spin flip issue

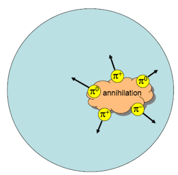
Two ways to search for ΔB=2 processes

- Free vs bound neutron oscillation: later → (NN→$\pi' s$)



time 10^{33} years

- a neutron oscillates into an antineutron

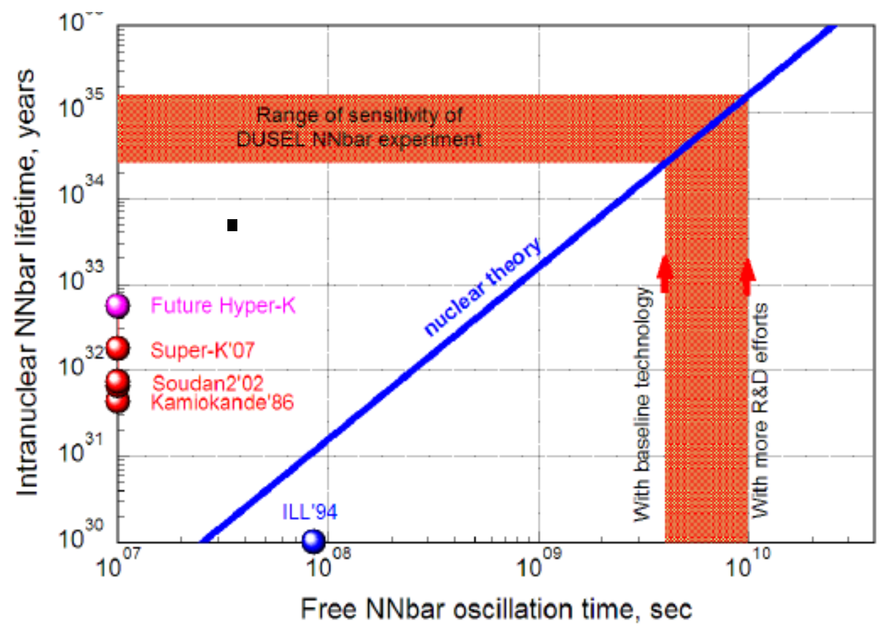


time ~5 x10^{-24} seconds

- the antineutron annihilates with another nucleon → pions

$$\tau_{Nuc} = R\tau^2_{free}$$

$$R = 0.3\times10^{23}\ \sec^{-1}$$



(Plot by Y. Kamyshkov)

$\tau_{n\bar{n}}$ > 2.44x10^8 sec. (S-K,Abe et al.)

- Free oscillation search much more effective !!